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MEMORANDUM

From: Bill Jemison
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Subject: Progress Report –
Progress Report (1/1/2014– 3/31/2014).

This document provides a progress report on the project “Advanced Digital Signal Processing for Hybrid Lidar” covering the period of 1/1/2014– 3/31/2014.

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Progress

Background

Hybrid lidar-radar ranging systems experience two main challenges from operating in the underwater channel that degrade system performance, as shown in Figure 1. The first of these is absorption, which occurs when a photon emitted from the laser is absorbed by water molecules or dissolved materials. Absorption causes the received signal level to decrease. The use of blue wavelengths in open ocean or green wavelengths in coastal ocean can be used to minimize absorption. The second challenge occurs due to scattering, in which photons are deflected out from the collimated laser beam after colliding with particles in the channel. Scattering degrades resolution and reduces range accuracy. In addition, if a sufficiently large amount of photons scattered back into the receiver field of view, this can cause the system to erroneously detect an “object” at the center of the scattering distribution rather than detecting the desired object. Scattering has typically been mitigated by applying high modulation frequencies to the laser, as backscatter has been shown to have a lowpass frequency response [1,2]. In terms of backscatter reduction, *this work will focus on the application of digital signal processing algorithms to improve performance by processing the received signal rather than depending solely on the physics of the underwater channel.*

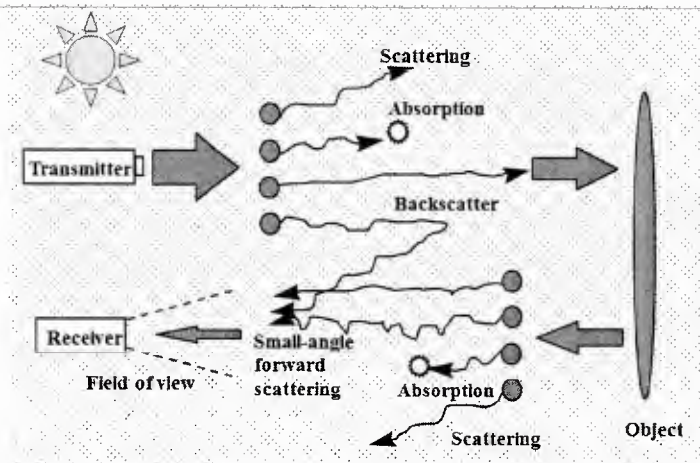


Figure 1. Sketch of water channel effects on hybrid lidar radar system

Although absorption and scattering are two separate physical phenomena, their effects on water conditions are often combined together into a single parameter, the attenuation coefficient c , which has units of m^{-1} . Beam attenuation in water follows an exponential decay law

$$P(c, z) = P_0 e^{-cz}$$

where z is the distance to the object and P_0 is the transmitted signal power. The product cz in the exponent is referred to as the number of attenuation lengths (a.l.), which is a dimensionless parameter used to compare ranging performance in different water conditions and at different distances.

Current Ranging Approaches

This section will briefly discuss two previous ranging approaches developed by Laux et al. [3] that were evaluated in the beginning of this work and serve as a baseline for our work. These approaches both work by modulating the laser and measuring the phase shift between the transmitted and received signals to compute the range. In the single frequency continuous wave (CW) hybrid lidar-radar approach, the laser

is modulated with a single frequency. As a result, the performance of this method is defined by the wavelength of this modulation frequency.

This results in a number of tradeoffs, which are summarized in Table 1. CW ranging cannot simultaneously achieve high unambiguous range and high range accuracy. Additionally, there is a tradeoff between unambiguous range and backscatter suppression.

Table 1. Tradeoffs for single frequency CW method

Modulation frequency	Unambiguous range	Range accuracy	Backscatter suppression
Low	High	Low	Low
High	Low	High	High

The tradeoffs with the single frequency approach motivated the Navy to develop the dual frequency CW approach, in which the ranging performance depends on the difference between the two modulation frequencies. This allows the dual frequency approach to be operated with two modulation frequencies high enough to be above the backscatter cutoff point. This method still has performance tradeoffs to be concerned with, which are summarized in Table 2. As with the single frequency approach, there is a tradeoff between high unambiguous range and high range accuracy.

Table 2. Tradeoffs for dual frequency method

Difference frequency	Unambiguous range	Range accuracy	Backscatter suppression
Low	High	Low	High
High	Low	High	High

The CW techniques will serve as a baseline for new signal processing techniques that have been developed under this program.

FDR – A New LIDAR Ranging Approach

In an attempt overcome the unambiguous range and range precision tradeoffs described previously, we have adapted a technique from the fiber optic community known as frequency-domain reflectometry (FDR). Utilizing modulation bandwidths of several gigahertz, this method has been used by the fiber optics community to unambiguously range over several kilometers of fiber optic cable with range resolutions on the order of 10 to 20 centimeters. Thus we aim to adapt this technique for hybrid lidar-radar in order to obtain centimeter-order accuracy and extended unambiguous ranging.

The key steps behind the FDR method are shown in Figure 2. First, a stepped-frequency signal is transmitted into the channel. A photo-detector converts the optical signal into an electrical signal, which is digitized and demodulated by the receiver. The digitized signal is then processed with common DSP algorithms. The CORDIC (COordinate Rotation DIgital Computer) algorithm is used to perform a coordinate transform to convert the in-phase (I) and quadrature (Q) components of the return into amplitude and phase. A complex frequency spectrum is constructed using the amplitude and phase of each modulation frequency used. The frequency spectrum is used as the input to the inverse Fast Fourier Transform (IFFT), to obtain time-domain information similar to what would be seen in a pulse return signal. An automated peak detection algorithm can then determine which peak in the return corresponds to an object, and outputs the corresponding range position. In turbid water, the FDR technique can simultaneously detect both the desired object and the volumetric backscattering region (Illig et al., 2013).



Figure 2. The FDR approach uses stepped frequency modulation and common DSP algorithms to compute range to an object.

A set of experiments were performed using the 3.6 m tank at Patuxent River Naval Air Station in January to validate the FDR technique. The experimental setup used to test the dual frequency and FDR ranging approaches is shown in Figure 3. The output from a RF signal generator is combined with a DC source to modulate the current of a 442 nm laser diode. The modulation depth of this diode was previously characterized for the 500 MHz bandwidth that is used in this work [4]; this information was used to calibrate out the effects of modulation depth in the experiments. The modulated light was transmitted through a window into a 3.6 m long tank to a diffuse reflector target mounted on a translation stage. The target was moved in 10 cm increments from a range of 1.35 m to 3.05 m. The optical receiver collected light scattered from the submerged target through the window. The front-end optics on the photomultiplier tube (PMT) optical receiver consisted of a 2" 442 nm interference filter followed by a 2", f/2 lens. An iris is used to adjust the aperture of the PMT; it was fixed at 10 mm for these experiments, giving a receiver field of view measured to be approximately 4 degrees (half-angle) in water. A bias-tee at the output of the PMT separated the DC and AC components of the photocurrent. The DC-coupled signal was monitored on a multimeter to ensure that the PMT remained within its linear operating regime. The AC-coupled signal was demodulated and digitized in the SDR receiver. The I and Q samples obtained by the SDR are transferred over an Ethernet cable to a PC, where the data are processed in a custom LabVIEWTM program.

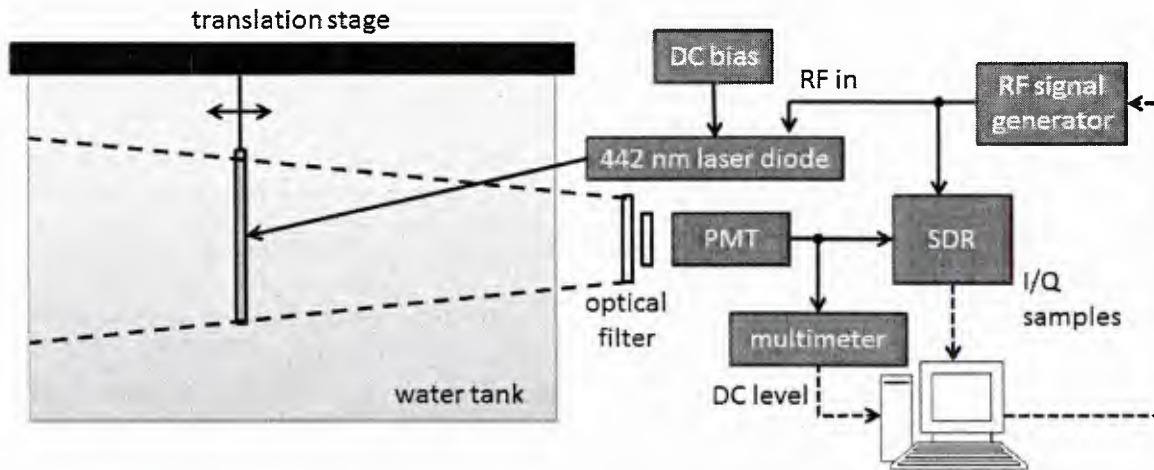


Figure 3. Block diagram of setup for FDR ranging experiments. A 442 nm laser diode is modulated with a stepped frequency waveform, modulated light is transmitted to an underwater object, and a PMT collects reflected light. The I/Q samples are generated by the SDR receiver and used to compute range on a PC.

Ranging results from the FDR experiments and RangeFinder simulations are shown in Figure 4. The FDR configuration divided a 500 MHz bandwidth from 50 to 550 MHz into 126 equally spaced tones with a 4 MHz spacing. A 400 MHz single frequency tone was used to enhance the range accuracy by smoothing out the "quantized range" calculated by FDR alone. In general, there is strong agreement between the simulated and experimental results. The simulated results suggest performance out to 10.8 attenuation lengths, while the experimental measurements actually obtained performance out to 10.2 attenuation lengths. The results have been subdivided into four regions based on the target-to-backscatter ratio; the target-to-backscatter ratio is shown in the simulated result on a second y-axis. In the first region, the target-to-backscatter ratio exceeds 30 dB and as a result the FDR algorithm computes the range with very low range errors: the mean error in this region is 1.2 cm. In the second region, the target-to-backscatter ratio is between 15 and 30 dB, with the range error approximately doubling and a mean value of 2.79 cm.

The target-to-backscatter ratio is between 0 and 15 dB in the third region, with a very small ripple appearing due to interference between the target and backscatter returns. Mean range error in this region is 3.47 cm. Finally, in the fourth region, the target-to-backscatter ratio is below 0 dB, and in this region the automatic peak detection portion of the FDR algorithm detects the backscatter peak instead of the target peak. As such, this region has extremely large range errors as is not detecting the target, resulting in a mean range error of 245 cm.

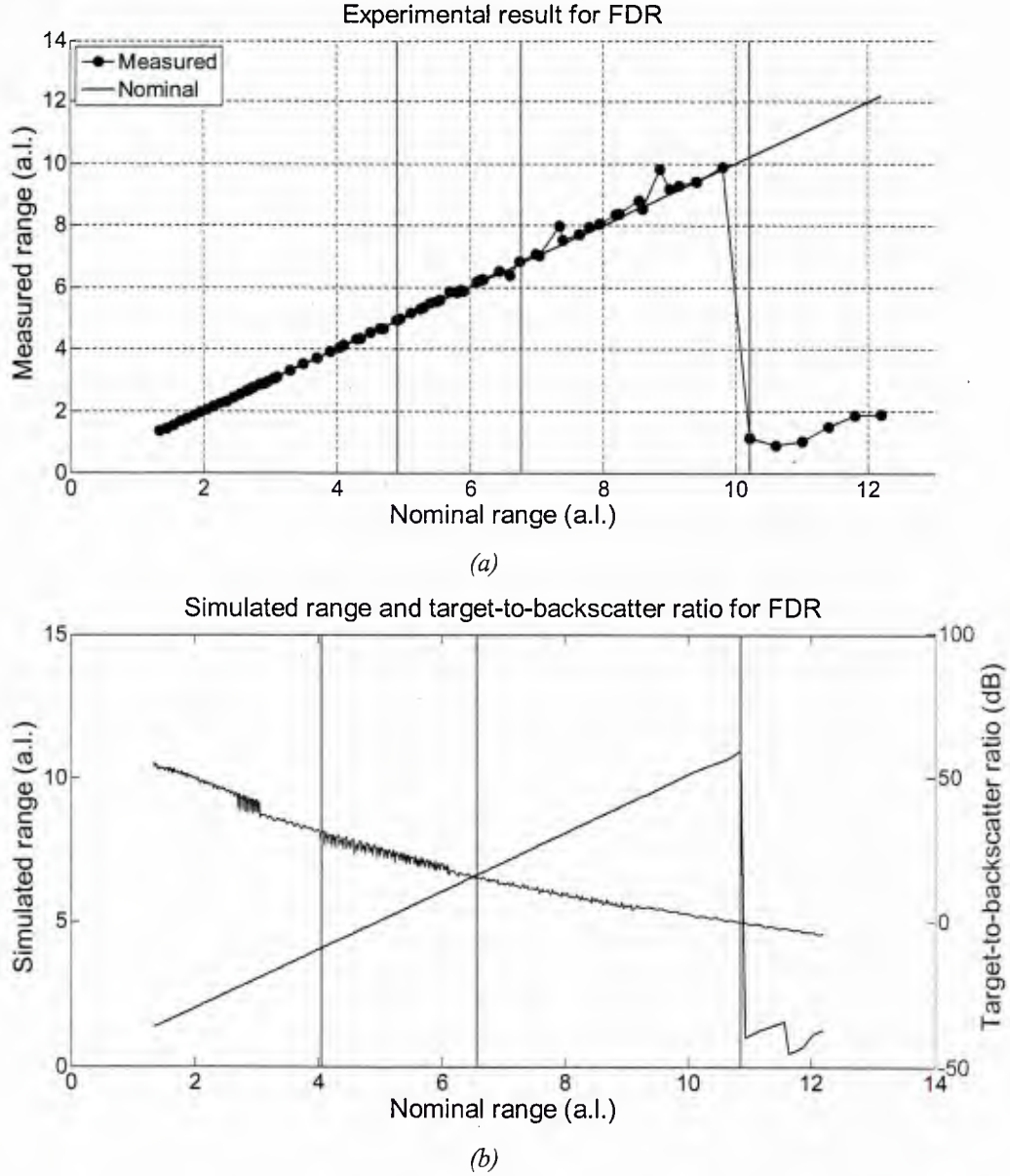


Figure 4. FDR ranging results for (a) experiment and (b) simulation show object tracking for over 10 attenuation lengths downrange. Object tracking is lost when target-to-backscatter ratio falls below 0 dB.

Blind Signal Separation

For the FDR ranging approach, the statistical signal processing technique of blind signal separation (BSS) was adapted for backscatter reduction. In this technique, data are transformed into a statistical domain in which signals are separated based on their statistical properties [5]. This is analogous to using the Fourier transform to transform data into the frequency domain and separate signals based on their frequency content. Unlike the spatial filtering approach, BSS does not need to be adjusted for every modulation

frequency, which made it a much more practical approach for backscatter suppression for the multiple frequencies required in the FDR method. A schematic of the BSS approach is shown below in Figure 5. In the top left, the frequency signal measured by FDR is shown, which contains both backscatter and target information. When this frequency signal is converted to range data, peaks for both the distributed backscatter and the target (correct location indicated with vertical green line) are obtained as shown in the top right. When BSS is applied to the frequency data, the scenario shown in the bottom left occurs, where the backscatter and target signals have been separated. By “zeroing out” the backscatter component, the range plot of the bottom right can be obtained, where the target still shows up in the correct position but the backscatter peak has been reduced by almost 10 dB. The BSS processing steps are critical in developing an automated target detection algorithm, such that the algorithm only detects a single peak instead of being confused by the backscatter return.

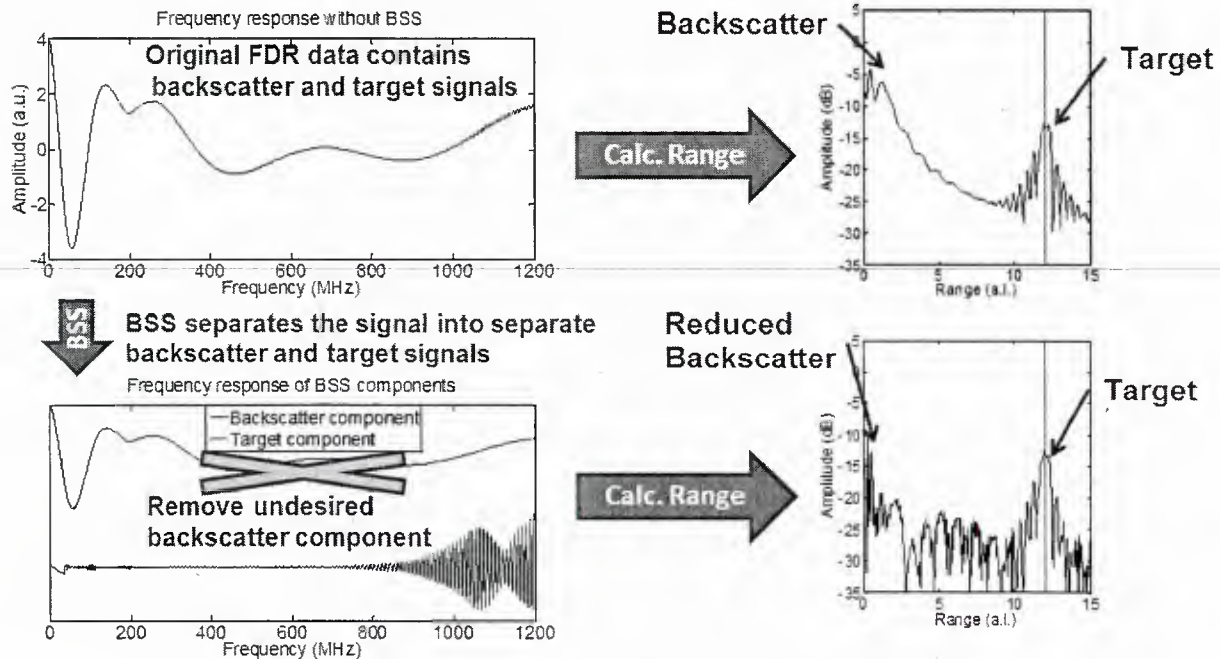


Figure 5. Schematic demonstrating approach for FDR with BSS

Blind signal separation has been applied to the data collected in the January experiments, with ranging results shown below in Figure 6. In this case, the experimental results showed object tracking out to 14.7 attenuation lengths downrange, while the simulation predicts some degree of performance out to at least 18 attenuation lengths. However, at this long distance, the 400 MHz single frequency has become scatter-limited, such that the “quantized” behavior of FDR appears in the simulated ranging results between 15-18 attenuation lengths. The difference between the experimental and simulated results is believed to be a result of the RangeFinder tool not modeling certain aspects of real hardware, such as receiver sensitivity and signal-to-noise ratio. In terms of range error, the mean range error in the object-tracking region of the experimental data is approximately 3 cm. This provides a reassurance that the blind signal separation technique does not affect the range calculated in scenarios where the target-to-backscatter ratio is high.

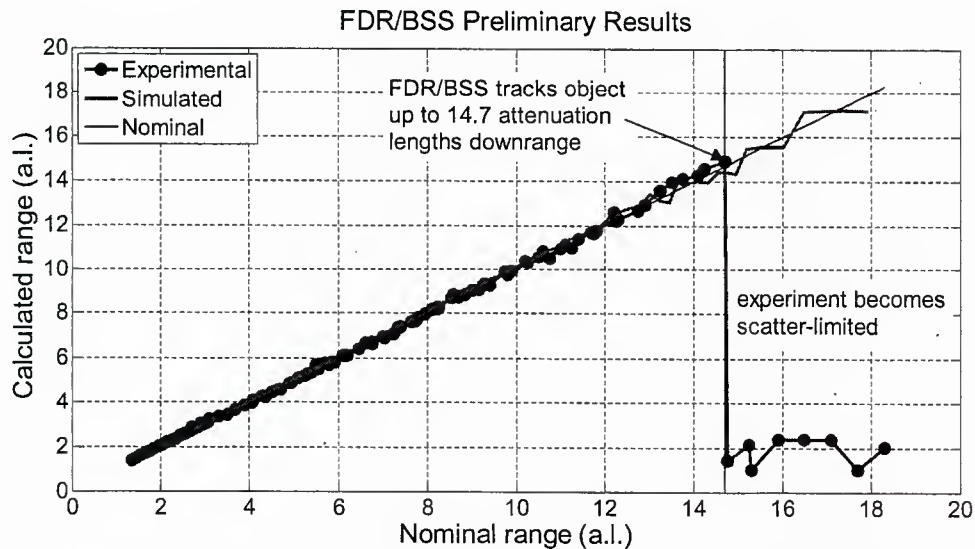


Figure 6. Ranging results for BSS experiment show object tracking to nearly 15 attenuation lengths downrange

A specific example of the effects of BSS on a single FDR range return is shown in Figure 7. The scenario shown is for an object position of $z=3.05$ m and a turbidity of $c=4$ m⁻¹, for an attenuation length of $cz=12.2$. This position is in the scatter-limited region when using FDR alone, but is correctly detected once blind signal separation is applied. The reason for this is the substantial improvement in the target-to-backscatter ratio: for FDR alone, this scenario has a target-to-backscatter ratio of approximately -6 dB and, as a result, detects the distributed backscatter instead of the object. Blind signal separation “learns” the backscatter response so that it can be cancelled out of the data. This results in a target-to-backscatter ratio of approximately 50 dB and a correct detection of the object position.

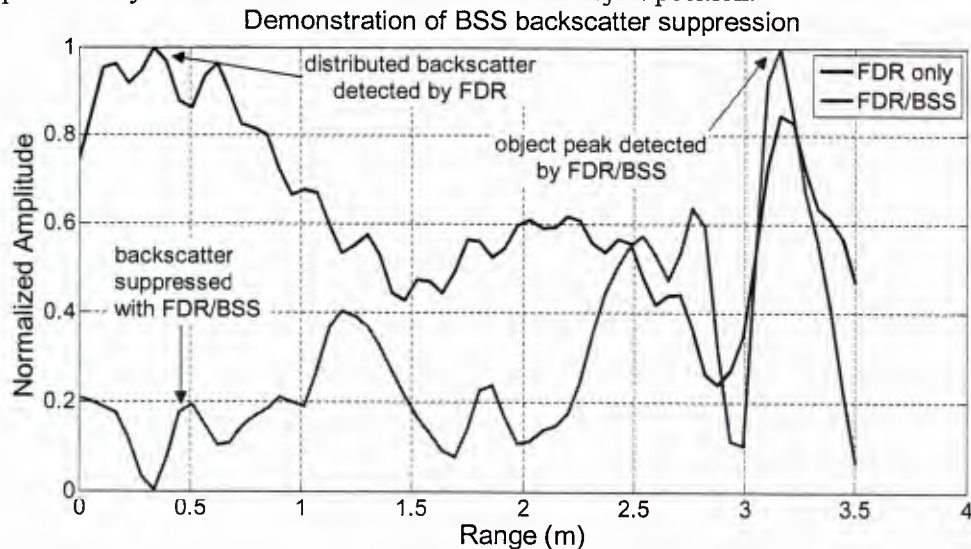


Figure 7. Demonstration of backscatter suppression performed by BSS: FDR (blue) detects the backscatter, while the object is detected with FDR/BSS (red)

Deployment to Real-Time Systems

The second objective of this project is to deploy these ranging algorithms onto real-time digital signal processing (DSP) systems. Progress is summarized below in Table 3, where an X represents a completed task and the empty cells indicate remaining work. At this point the background information for each technique has been developed and small-scale experiments have been performed for each technique. Large-scale tank experiments have been completed for the single-tone, dual-tone, spatial filter, FDR, and blind

signal separation techniques. Real-time code has been designed for most of the techniques, with the code written and simulated in the Xilinx environment for the single-tone and dual-tone ranging algorithms. The next step will be to deploy these codes to an embedded system, at which point experiments will be performed to both validate the hardware system and to verify that the system produces meaningful results. Once the single-tone and dual-tone algorithms have been experimentally verified on real-time DSP hardware, the FDR algorithm will be developed and tested on the DSP hardware platform. The major focus will be on deploying the ranging algorithms to the DSP hardware platform, with the secondary goal being to also deploy the backscatter suppression algorithms. The methods will be compared in terms of both experimental performance and also resource utilization on the DSP hardware platform.

Table 3. Summary status of ranging algorithms

		Single-tone	Dual-tone	FDR	FDR/CW	Single-tone + spatial filter	Dual-tone + spatial filter	FDR + BSS
Background	Theory	X	X	X	X	X	X	X
	Simulation	X	X	X	X	X	X	X
Experimental Investigation	Proof-of-concept	X	X	X	X	X	X	X
	Small-scale (benchtop)	X	X	X	X	X	X	X
	Large-scale (tank)	X	X	X	X	X	X	X
Real-Time Implementation	Code design	X	X	X	X	X	X	
	Simulation	X	X	X				
	Implementation	X	X	X				
	Real-time experiment	Apr.	Apr.	Apr.				

Planned work and summary

Experiments are planned to verify real-time versions of each of the ranging algorithms developed in this work. Currently it appears that backscatter suppression techniques will be applied in post-processing to the results of these experiments.

The new FDR ranging approach has been shown to range out to 10.2 attenuation lengths in laboratory experiments. The addition of blind signal separation for backscatter suppression pushed performance out to 14.7 attenuation lengths. Due to the ability to distinguish between the object and backscatter returns, the range errors in both the FDR and FDR/BSS experiments are on the order of a few centimeters. These results show that an algorithm has been developed to meet the goals of centimeter-order accuracy and extended unambiguous ranging.

References

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